

EXCITED DARK MATTER VERSUS PAMELA/FERMI

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Excitation of multicomponent dark matter in the galactic center has been proposed as the source of low-energy positrons that produce the excess 511 keV γ rays that have been observed by INTEGRAL. Such models have also been promoted to explain excess high-energy e^\pm observed by the PAMELA, Fermi/LAT and H.E.S.S. experiments. We investigate whether one model can simultaneously fit all three anomalies, in addition to further constraints from inverse Compton scattering by the high-energy leptons. We find models that fit both the 511 keV and PAMELA excesses at dark matter masses $M < 400$ GeV, but not the Fermi lepton excess. The conflict arises because a more cuspy DM halo profile is needed to match the observed 511 keV signal than is compatible with inverse Compton constraints at larger DM masses.

1 Galactic cosmic ray anomalies and DM collisions

There are several hints of unexplained sources of electrons and positrons in our galaxy, which could be due to collisions of dark matter (DM). The longest-standing one is the excess of 511 keV γ rays from the galactic center, first seen by balloon-borne detectors in the 1970's, and most recently measured by the SPI spectrometer aboard the INTEGRAL satellite (for a review, see ref.¹). More recently, a number of experiments have found evidence for e^\pm at higher energies, in excess of those understood to be coming from known sources. Among these, PAMELA² reports an excess in the positron fraction at energies of 10 – 100 GeV, while the Fermi Large Area Telescope (LAT)³ and H.E.S.S.⁴ observe an excess of $e^+ + e^-$ in the 100 – 1000 GeV energy range.

Although many different astrophysical explanations have been proposed as the source of the low-energy positrons that produce the 511 keV signal, there is no consensus.^a Pulsars have

^afor example, the argument of ref.⁵ that low-mass x-ray binaries are most likely source has been criticized in

been proposed as a likely source of the PAMELA and Fermi leptons (see for example refs. ^{7,8}) but the uncertainties in the parameters characterizing such sources still leave room for other interpretations.

Although DM annihilations had previously been suggested as the source of some of these anomalies, ref. ⁹ was the first to point out a class of DM models that could potentially explain all of them (and a few others: the WMAP haze and the DAMA/LIBRA annual modulation). Namely, these are models where the DM has a mass M near the TeV scale, and has several components that acquire naturally small mass splittings $\delta M \lesssim 1$ MeV from radiative corrections. A new hidden sector Higgs or gauge boson with mass $\mu \lesssim 1$ GeV mediates annihilations of the DM into e^\pm but not antiprotons (since $\mu < 2m_p$), of which no excess has been observed by PAMELA. All of this can be economically achieved by assuming the hidden sector gauge symmetry is nonabelian and spontaneously breaks near the GeV scale. Then the mediator is one of the gauge bosons B_μ , which can mix with the standard model hypercharge Y_μ through the dimension-5 gauge kinetic mixing operator $\Lambda^{-1} \Delta^a B_{\mu\nu}^a Y^{\mu\nu}$, where Δ^a is a hidden sector Higgs field in the adjoint representation that gets a VEV. Some of the simplest examples involving SU(2) gauge symmetry were considered by us in ref. ^{10,11}.

$$\begin{array}{l} \chi_3 \\ \chi_2 \\ \delta M_{23} \sim 100 \text{ keV} \\ \delta M_{12} \gtrsim 1 \text{ MeV} \\ \chi_1 \end{array}$$

Figure 1: Inverted mass hierarchy for excited DM states.

2 Exciting Dark Matter in the Galactic Center

The excited DM mechanism (XDM) for explaining the 511 keV excess was first proposed in ref. ¹³. The ground state DM particles undergo inelastic scattering to the excited state by $\chi_1 \chi_1 \rightarrow \chi_2 \chi_2$, followed by decays $\chi_2 \rightarrow \chi_1 e^+ e^-$ into nonrelativistic e^\pm . However a quantitative computation of the excitation cross section was not used there, and ref. ¹⁴ argued that the rate of excitation was too small to account for the observations unless many partial waves were at their maximum values allowed by unitarity.

In refs. ^{10,12} we numerically computed the excitation cross section by solving the Schrödinger equation, and showed that indeed the suspicion of ref. ¹⁴ was correct, the rate of e^+ production is too small, even varying all the model parameters and DM halo properties over a wide range. At the same time, we proposed a solution, involving the existence of a stable excited state that undergoes scattering $\chi_2 \chi_2 \rightarrow \chi_3 \chi_3$, followed by the decay $\chi_3 \rightarrow \chi_1 e^+ e^-$. This can have a smaller mass gap $\delta M_{23} \sim 100$ keV which is easier to excite in DM collisions than the larger one $\delta M_{13} > 2m_e$. This “inverted mass hierarchy” is shown in figure 1.

Figure 2 (left panel) shows an example of our new contours for the rate of positron production compared to the observed rate in the M - μ plane,¹⁸ using the mass splitting $\delta M_{23} = 100$ keV, and the gauge coupling $\alpha_g = 0.031$ (M/TeV) required for getting the right relic density.¹¹ The DM density profile is taken to be of the Einasto form,

$$\rho = \rho_\odot \exp \left[-\frac{2}{\alpha} \left(\left(\frac{r}{r_s} \right)^\alpha - \left(\frac{r_\odot}{r_s} \right)^\alpha \right) \right] \quad (1)$$

with $\rho_\odot = 0.4$ GeV/cm³, $r_\odot = 8.3$ kpc, $\alpha = 0.17$, $r_s = 15$ kpc, consistent with best-fit values of N -body ref. ⁶.

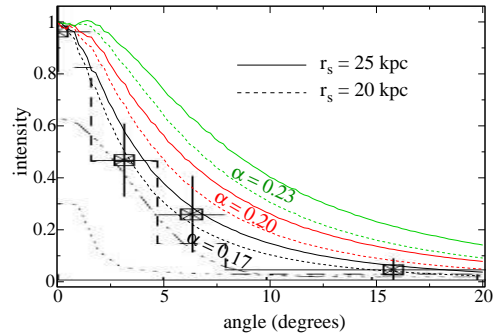


Figure 3: Observed angular distribution of INTEGRAL 511 keV signal, and theoretical predictions for different Einasto parameter values $\alpha = 0.17, 0.20, 0.23$, $r_s = 20, 25$ kpc.

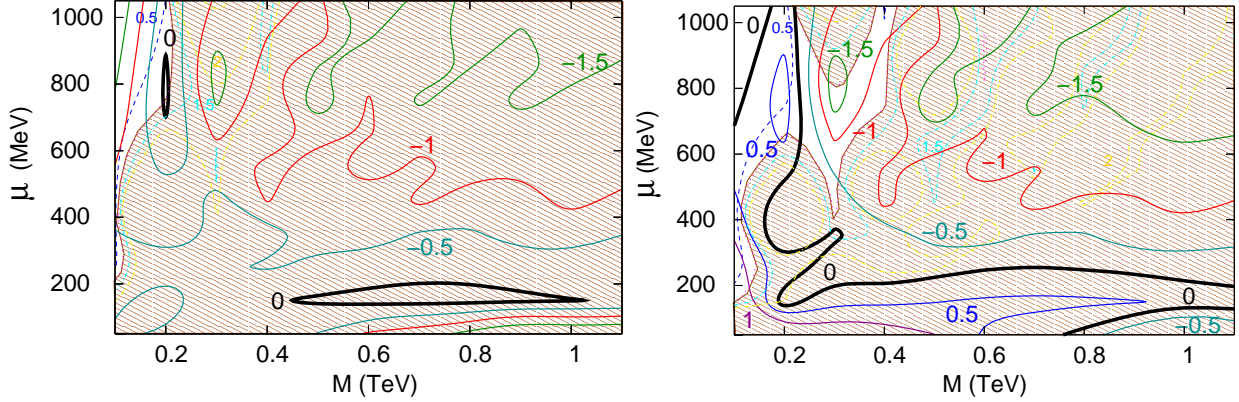


Figure 2: Left: contours of the rate of positron production, $\log(R_{e^+}/R_{\text{obs}})$ (for INTEGRAL 511 keV γ rays) in plane of gauge boson mass μ versus DM mass M for $\delta M_{23} = 100$ keV mass splitting and halo Einasto profile parameters $\alpha = 0.17$, $r_s = 15$ kpc, $\rho_\odot = 0.4$ GeV/cm³, $v_0 = 250$ km/s.¹⁸ Heavy contours match the observed rate. Dashed curves are contours of inverse Compton (IC) signal over IC bound. Shaded regions are excluded by IC constraint. Right: same, but with $\delta M_{23} = 25$ keV, $\alpha = 0.20$, $r_s = 15$ kpc, $\rho_\odot = 0.3$ GeV/cm³, $v_0 = 220$ km/s.

simulations,¹⁷ and a high value of the circular velocity $v_0 = 250$ km/s. In this example, the heavy contours show that there exist parameters leading to a large enough rate, but these tend to disappear rapidly if one increases the values of δM_{23} (since the χ_2 states do not have enough kinetic energy to produce χ_3), or α or r_s (since then ρ becomes too small in the central region of the galaxy, reducing the rate). This can be compensated by decreasing δM on the other hand, as illustrated in the right panel of fig. 2. The shaded regions are ruled out by constraints on inverse Compton gamma rays,¹⁶ as we discuss in the next section. Fig. 3 shows that the more cuspy DM profile with $\alpha = 0.17$ gives a better fit to the angular distribution of the 511 keV signal.

3 High energy e^\pm from annihilations

Although in refs.^{10,11} we showed that the XDM mechanism with inverted mass hierarchy can work for the 511 keV signal, we did not consider whether it could also be compatible with the PAMELA and Fermi lepton excesses. The same model can also explain the high energy leptons through annihilation to hidden sector gauge bosons, $\chi_1\chi_1 \rightarrow BB$, followed by the decays $B \rightarrow e^+e^-$ ¹⁵. However, this scenario has come under increasing pressure from various constraints, the most stringent being due to inverse Compton scattering of e^\pm on starlight in the galaxy, which should produce γ rays with energies up to several hundred GeV. Demanding that this new source not exceed recent observations excludes the annihilating DM interpretation of Fermi leptons unless the galactic DM density profile is less cuspy near the center¹⁶ than is generally expected on the basis of N -body simulations of halo evolution.¹⁷ This limit requires taking small values of $\delta M \lesssim 100$ keV in order to get a large enough rate for 511 keV γ rays, as illustrated in fig. 2.

The ability of the models to explain the high-energy lepton observations while respecting the IC constraints are summarized in figure 4 taken from ref.¹⁹. The left figure is an example using a cuspy halo profile compatible with the PAMELA and 511 keV excesses, at $M < 400$ GeV, while the right one shows the result of a noncuspy profile where the PAMELA and Fermi excesses can be marginally explained, but not the 511 keV.

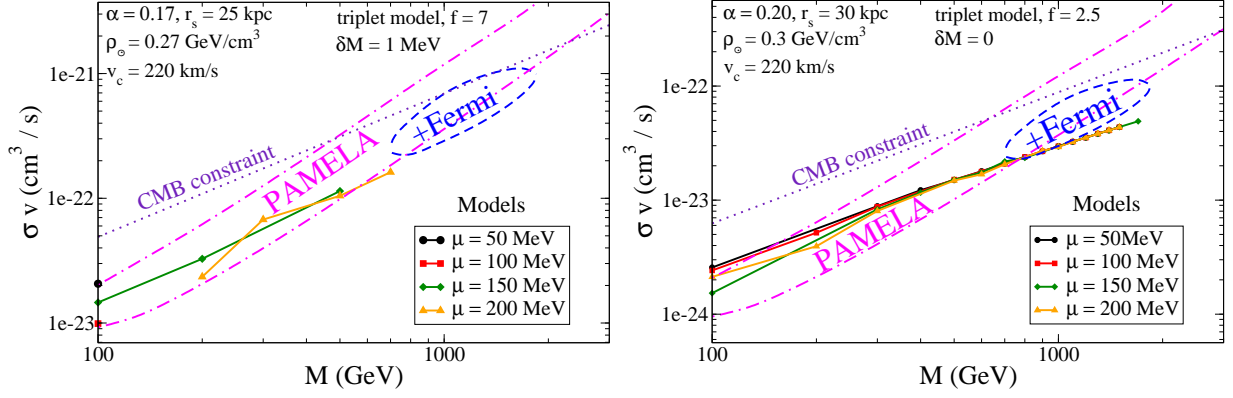


Figure 4: Allowed regions for PAMELA and Fermi lepton excess in σv - M plane,¹⁹ and predictions of multistate DM annihilation that are compatible with inverse Compton constraint. Left: for Einasto parameters $\alpha = 0.17$, $r_s = 25$ kpc, $\rho_\odot = 0.28$ GeV/cm³; Right: for $\alpha = 0.20$, $r_s = 30$ kpc, $\rho_\odot = 0.3$ GeV/cm³. $1/f$ is fraction of total DM mass density occupied by annihilating DM ground state χ_1 .

4 Conclusions

We have found that annihilating multistate DM can explain two out of three galactic cosmic ray anomalies, either PAMELA/Fermi or PAMELA/INTEGRAL, but not all three simultaneously. Although it is possible to marginally predict all the correct rates using Einasto profile parameter $\alpha = 0.20$, the angular distribution of 511 keV γ rays is too wide in this case. Of the two possibilities, the PAMELA/INTEGRAL combination seems preferable from the standpoint of the required DM halo parameters, since in this case we are able to adopt standard values that are quite compatible with N -body simulations of galactic structure evolution. Moreover we can match the anomalous lepton rates well for PAMELA/INTEGRAL. The PAMELA/Fermi possibility requires stretching the halo parameters to their maximal values, while only marginally giving a large enough rate of leptons, yet a small enough rate of associated inverse Compton γ rays.

References

1. R. Diehl and M. Leising, arXiv:0906.1503.
2. O. Adriani *et al.* [PAMELA Collaboration], Nature **458**, 607 (2009) [arXiv:0810.4995].
3. A. A. Abdo *et al.* [Fermi LAT Collaboration], Phys. Rev. Lett. **102**, 181101 (2009) [arXiv:0905.0025].
4. F. Aharonian *et al.* [H.E.S.S. Collaboration], [arXiv:0905.0105].
5. G. Weidenspointner *et al.*, Nature **451**, 159 (2008).
6. R. M. Bandyopadhyay, J. Silk, J. E. Taylor and T. J. Maccarone, [arXiv:0810.3674].
7. D. Hooper, P. Blasi and P. D. Serpico, JCAP **0901**, 025 (2009) [arXiv:0810.1527].
8. D. Grasso for the Fermi-LAT collaboration, arXiv:0907.0373.
9. N. Arkani-Hamed, *et al.*, Phys. Rev. D **79**, 015014 (2009) [arXiv:0810.0713].
10. F. Chen, J. M. Cline and A. R. Frey, Phys. Rev. D **79**, 063530 (2009) [arXiv:0901.4327].
11. F. Chen, J. M. Cline and A. R. Frey, Phys. Rev. D **80**, 083516 (2009) [arXiv:0907.4746].
12. F. Chen, J. M. Cline, A. Fradette, A. R. Frey and C. Rabideau, Phys. Rev. D **81**, 043523 (2010) [arXiv:0911.2222].
13. D. P. Finkbeiner and N. Weiner, [arXiv:astro-ph/0702587].
14. M. Pospelov and A. Ritz, Phys. Lett. B **651**, 208 (2007) [arXiv:hep-ph/0703128].
15. P. Meade *et al.*, Nucl. Phys. B **831**, 178 (2010) [arXiv:0905.0480].
16. M. Papucci and A. Strumia, [arXiv:0912.0742].

17. J. F. Navarro *et al.*, arXiv:0810.1522.
18. F. Chen, J. Cline, A. Frey, “Stable excited dark matter and galactic 511 keV γ rays,” in preparation.
19. M. Cirelli and J. M. Cline, arXiv:1005.1779 [hep-ph].